LATERAL RIDE QUALITY OF THE B-1

AIRCRAFT SUBJECTED TO A REDUCTION OF

LATERAL STATIC STABILITY

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ABSTRACT

A method to evaluate the lateral ride quality of a B-1 aircraft subjected to a reduction in lateral static stability is developed. Ride quality is then found for three different relaxed static stability configurations which are augmented by yaw rate feedback to restore specified handling qualities. These cases are compared to the ride quality of the unrelaxed aircraft with the same handling qualities.

NOMENCLATURE

b	wing span
C_y	side force derivative
C_n	yawing moment derivative
g	gravity
ℓ_x	distance from CG, positive forward, ft.
n_y	lateral load factor, g's
U_0	aircraft forward velocity.
β	sideslip angle
ψ	yaw angle
ϕ	roll angle
ϕ_j	elastic mode shapes
ξ_j	elastic mode generalized coordinates
η	unit white noise
ζ_d	dutch roll damping
ω_d	dutch roll natural frequency

SUBSCRIPTS

B	body

V vertical tail

X body station

W wing

g gust

δ_r rudder deflection

INTRODUCTION

With the advent of control configured vehicles, the aircraft industry seems to be on the verge of a new generation of aircraft which are more fuel-efficient, lighter, and have more desirable handling qualities throughout their flight envelopes. On a large transport aircraft, relaxed static stability (RSS) allows more aft CG locations and reduced empennage size with resulting weight and drag savings, using a stability augmentation system (SAS) to restore acceptable handling qualities.

One question which remains to be answered is what effect a reduction in static stability would have on the ride quality of a large, highly elastic control-configured vehicle. This paper presents the results of an investigation into the lateral ride quality of the Rockwell International B-1 aircraft when it is subjected to a reduction in the lateral static stability. The ride quality parameter used is the rms response at selected stations on the fuselage centerline. The problem is formulated entirely in the time domain using state vector and matrix operations.

RIDE QUALITY EQUATIONS

In terms of the perturbation roll angle ϕ; sideslip angle β; yaw angle ψ; antisymmetric elastic mode shapes and coordinates ϕ_j and ξ_j; and steady state forward velocity U_0, the lateral normal acceleration load factors as a function of fuselage station ℓ_x (positive forward of the C.G.) is

$$n_y(\ell_x,t) = \frac{1}{g}[g\phi - (\dot{\beta}+\dot{\psi})U_0 - \ell_x\ddot{\psi} - \sum_{j=1}^{m} \phi_j(\ell_x)\ddot{\zeta}_j(t)] \quad (1)$$

The aircraft equations of motion are written in state vector form

$$\dot{x} = Ax + Bu + G\,\eta_g \quad (2)$$

where x is an (nx1) matrix of the aircraft physical variables, u is an (mx1) matrix of control inputs, and η_g is a (kx1) matrix of the gust velocity state variables. A, B, and G are (nxn), (nxm), and (nxk) coefficient matrices, respectively. η is scalar, zero mean unit white noise, and η_g satisfies the equation[1]

$$\dot{\eta}_g = A_g\,\eta_g + G_g\,\eta \quad (3)$$

Thus, the state equation (2) can be rewritten as (4) by augmenting the state vector x with the gust states

$$\begin{bmatrix} \dot{x} \\ \dot{\eta}_g \end{bmatrix} = \left[\begin{array}{c|c} A & G \\ \hline 0 & A_g \end{array}\right] \begin{bmatrix} x \\ \eta_g \end{bmatrix} + \left[\begin{array}{c} B \\ \hline 0 \end{array}\right] u + \begin{bmatrix} 0 \\ G_g \end{bmatrix} \eta \quad (4)$$

Since most feedback laws can be expressed as

$$u = -Kx \quad (5)$$

equation (4) can be rewritten as

$$\begin{bmatrix} \dot{x} \\ \dot{\eta}_g \end{bmatrix} = \left[\begin{array}{c|c} A-BK & G \\ \hline 0 & A_g \end{array}\right] \begin{bmatrix} x \\ \eta_g \end{bmatrix} + \begin{bmatrix} 0 \\ G_g \end{bmatrix} \eta \quad (6)$$

To simplify notation, let Equation (6) be

$$\dot{x}^* = Dx^* + F\eta \qquad (7)$$

Equation (1), the load factor equation, can be rewritten as

$$n_y(\ell_x,t) = Px^* \qquad (8)$$

where P is a deterministic row matrix (1xn+k) which makes n_y a scalar. The mean or expected value of n_y^2 is obtained by squaring and averaging.

With some simple algebraic manipulations, Equation (8) becomes

$$E[n_y^2(\ell_x,t)] = PE[x^* x^{*'}]P' \qquad (9)$$

where [ ]' denotes the matrix transpose and E[ ] denotes expected value. It can be shown[2] that $E[x^* x^{*'}]$, the (n+k) x (n+k) symmetric state covariance matrix, can be found from the solution of the algebraic matrix Riccati equation

$$\frac{d}{dt} E[x^* x^{*'}] = DE[x^* x^{*'}] + E[x^* x^{*'}]D' + FF' = 0 \qquad (10)$$

Equation (10) has a unique solution for a stable system, and can be solved numerically by a method described in reference 3.

RSS STABILITY DERIVATIVES

In order to calculate the effect of relaxed static stability on ride quality, it is first necessary to be able to find the changes in the aircraft stability derivatives resulting from the reduction of static stability. For the purposes of this study, it is assumed that for small changes in center of gravity (CG) location and small changes in vertical tail size (S_v), the elastic mode shapes of the airplane do not change appreciably. The stability derivatives which do change appreciably with relaxed static stability are the change in side force with sideslip angle, C_{y_β}; change in yawing moment with sideslip angle, C_{n_β}; change in yawing moment with yaw rate, C_{n_r}; and, if the rudder is assumed to be a constant percentage of the vertical tail area, change in side force with rudder deflection $C_{y_{\delta_r}}$; and change in yawing moment with rudder deflection $C_{n_{\delta_r}}$.

From references 4 and 5, it can be said that

$$C_{y_\beta} = C_{y_{\beta_W}} + C_{y_{\beta_B}} + C_{y_{\beta_V}} \tag{11}$$

It can be assumed that

$$C_{y_{\beta_W}} + C_{y_{\beta_B}} = \text{CONSTANT} \tag{12}$$

since neither the wing nor the body have been modified by moving the CG or changing S_V. With knowledge of the actual value of C_{y_β} at the particular flight condition of the B-1 under consideration (Mach .85, Sea Level), and knowing the geometry of the aircraft, a reasonable guess can be made as to how C_{y_β} changes with relaxed static stability. The result is given in equation (11) as

$$C_{y_\beta} = -.278 - (1.52 + 3.76 \frac{S_V}{S})\frac{S_V}{S} \tag{13}$$

a value of $\frac{S_V}{S} = 1.$ corresponds to the unrelaxed aircraft, and this equation gives the known value of this stability derivative. As $\frac{S_V}{S}$ is reduced, the magnitude of C_{y_β} is reduced.

A similar method was used to estimate the other stability derivatives, and the results are given in equations (14)-(17).

$$C_{n_\beta} = -.026 - (\frac{\ell_v}{b})(1.52 + 3.67 \frac{S_v}{S}) \frac{S_v}{S} \quad (14)$$

$$C_{n_r} = -.0533 + \frac{2\ell_v^2}{b^2} (1.52 + 3.67 \frac{S_v}{S}) \frac{S_v}{S} \quad (15)$$

$$C_{y_{\delta_r}} = (.0636) \frac{S_v}{S} \quad (16)$$

$$C_{n_{\delta_r}} = -(.0636)(\frac{\ell_v}{b})(\frac{S_v}{S}) \quad (17)$$

C_{y_β}, C_{n_β}, and C_{n_r} are used to modify the coefficient matrix A, $C_{y_{\delta_r}}$ and $C_{n_{\delta_r}}$ are used to modify the matrix B of equation (1) to give the equations of motion of the relaxed static stability modification of the aircraft.

YAW DAMPER IMPLEMENTATION

In order to restore the desired handling qualities to the relaxed stability aircraft, a simple yaw rate feedback to rudder is introduced. For most stability augmentation system (SAS) laws, the control input vector u can be expressed as

$$u = -Kx \quad (18)$$

where K is an (mxn) matrix of gains.

For this study, the state vector x is given by

$$x' = [\beta, \phi, \dot{\phi}, \dot{\psi}, \zeta_1, \dot{\zeta}_1, \zeta_2, \dot{\zeta}_2, \zeta_3, \dot{\zeta}_3, \zeta_4, \dot{\zeta}_4, v_g, v_{g_1}, p_g, r_g] \quad (19)$$

where ζ_i are the generalized coordinates of the first four lowest frequency antisymmetric elastic modes, and v_g, v_{g_1}, p_g and r_g are the sideslip, roll, and yaw gust states. There are a total of sixteen states in this model.

The aircraft can be controlled laterally by both aileron and rudder inputs, so the matrix B is (16x2). K is then a (2x16) matrix. It is desired, however, to feedback only yaw rate to rudder, the fourth element of the state vector. Therefore, K can be written as

$$K = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{24} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (20)$$

For a given aircraft configuration, an iterative procedure can be used to determine the value of K_{24} which gives the desired handling characteristics.

RESULTS

The lateral load factors of the B-1 aircraft, flying at Mach .85 at sea level, in response to a 1 ft/sec gust were found using the above described method. Figure 1 shows the results, with one curve representing the ride of the aircraft with the inclusion of the first four elastic modes, and a second curve showing the ride when the elastic modes are included in the equations of motion (Eq. 7) but not in the ride quality equation (Eq. 9). Note that the elastic effects have a very significant effect on the ride quality, which was expected in the case of the highly flexible B-1. Fortunately for the pilot, the crew compartment is located at approximately body station 372, where the ride is the best.

The lateral static stability of the aircraft was reduced by moving the center of gravity aft 5', and by reducing the vertical tail area by 30%. Yaw rate feedback was used to augment the stability of the three resulting RSS configurations (CG shift, reduced S_V, both together). The damping of the so-called "Dutch Roll" mode is generally considered to be most important parameter from the standpoint of lateral handling qualities. The RSS configurations were augmented to a "moderate" dutch roll damping of .19, and a "heavy" damping of .63. These results are presented in Figures 2 - 4. Note that the higher damping gives in general a better ride, with reductions in RMS load factor of about 20% at the tail. This result is in itself significant, and suggests that a higher damping of the dutch roll mode gives in general a better ride.

A comparison of the ride quality of the three RSS configurations at constant values of dutch roll damping reveal an interesting result. A reduction in vertical tail area gives a worse ride. For ζ_d = .19, the ride is 32% worse at the pilot's station, and 12% worse at the tail than the unrelaxed aircraft with the same damping. At ζ_d = .63, these values are 21% at the pilot station, and 7% at the tail. The RSS configuration with CG shift only changed very little from the unrelaxed airplane. For this reason and for the purpose of clarifying the graphs, the unrelaxed aircraft load factors are not shown. Adding the CG shift to the lowered tail area worsened the ride slightly. Table 1 gives some insight into why this occured.

TABLE 1. YAW DAMPER GAINS, DUTCH ROLL DAMPING RATIOS AND NATURAL FREQUENCIES.

	YAW DAMPER GAIN	ζ_d	ω_n, rad/sec
SHIFTED CG	3.1	.63	1.75
	.8	.19	1.93
REDUCED S_V	3.75	.63	1.10
	1.1	.19	1.53
FULLY RELAXED	4.0	.63	1.00
	1.4	.19	1.41
UNRELAXED A/C	2.7	.63	1.81
	.6	.19	1.99

Note that reduction in static stability leads to a lowering of the dutch roll natural frequency for constant damping. The results in Fig. 5 suggest that ride quality is dependent on frequency as well as damping ratio. For the same damping, the two RSS configurations with lowered tail size have both significantly higher load factors and significantly lower natural frequencies. The other RSS, the one which has only the CG shift, gave a slight improvement in overall ride over the unrelaxed aircraft, about 2% at pilot station and tail for $\zeta_d = .63$, and less than 1% for $\zeta_d = .19$.

If a full-state feedback system were to be implemented, both the damping and frequency of the dutch roll mode could be set to desired values. This would help to further define the effect of this frequency on ride quality. We are presently investigating this.

CONCLUSIONS

A parametric study on the effect of a reduction in lateral static stability on the lateral ride quality of the B-1 aircraft was performed. It was shown that in general an increase in "dutch roll" damping yields an improved ride. It was further shown that relaxing the static stability by an aft displacement of the CG can improve the ride quality slightly for the B-1. However, further research needs to be done in order to define the relative effects of dutch roll frequency and damping on the lateral ride quality, and we are continuing with this research.

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Fig 1. B-1 LATERAL LOAD FACTORS
BARE AIRFRAME , $\zeta_d = .08$

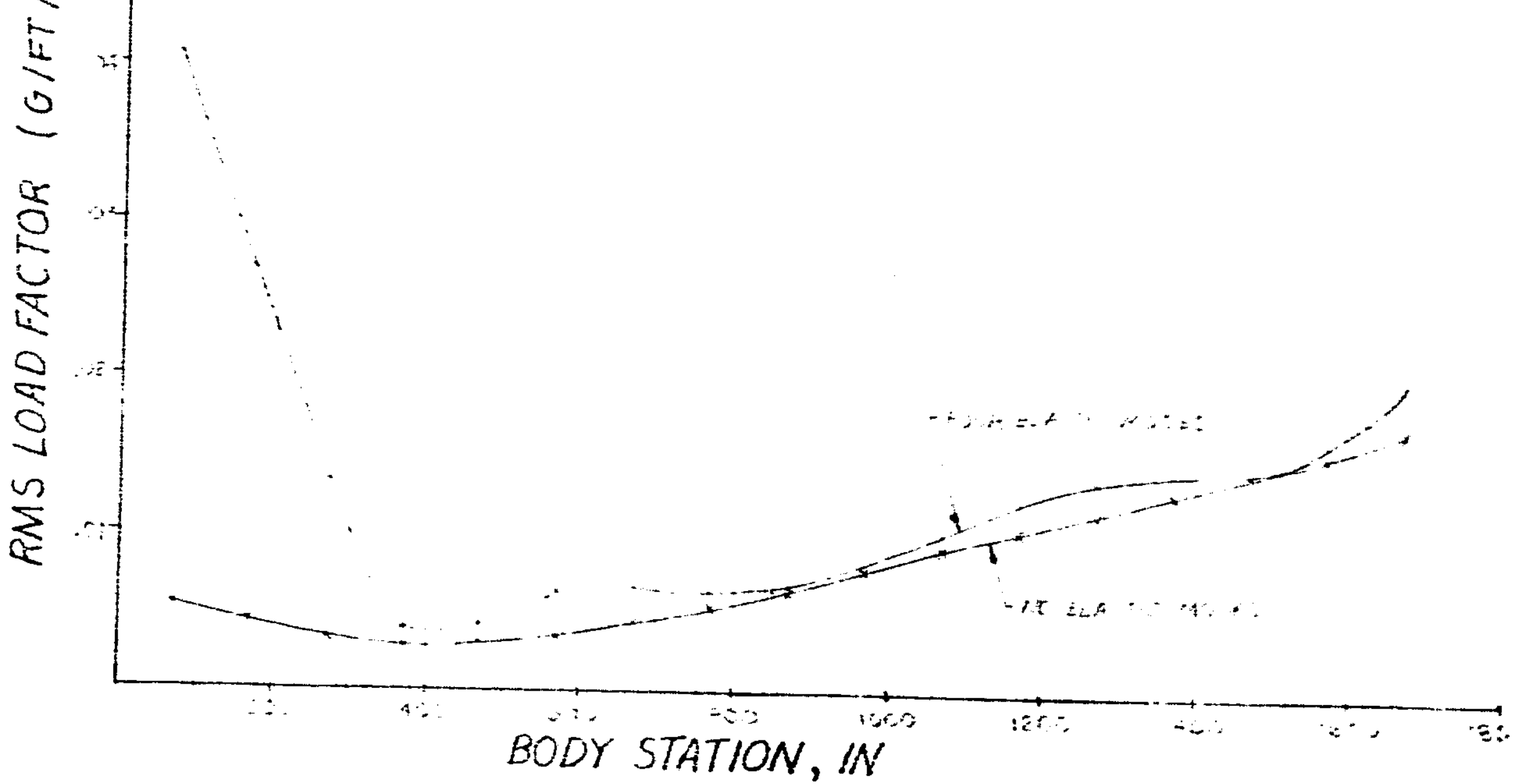
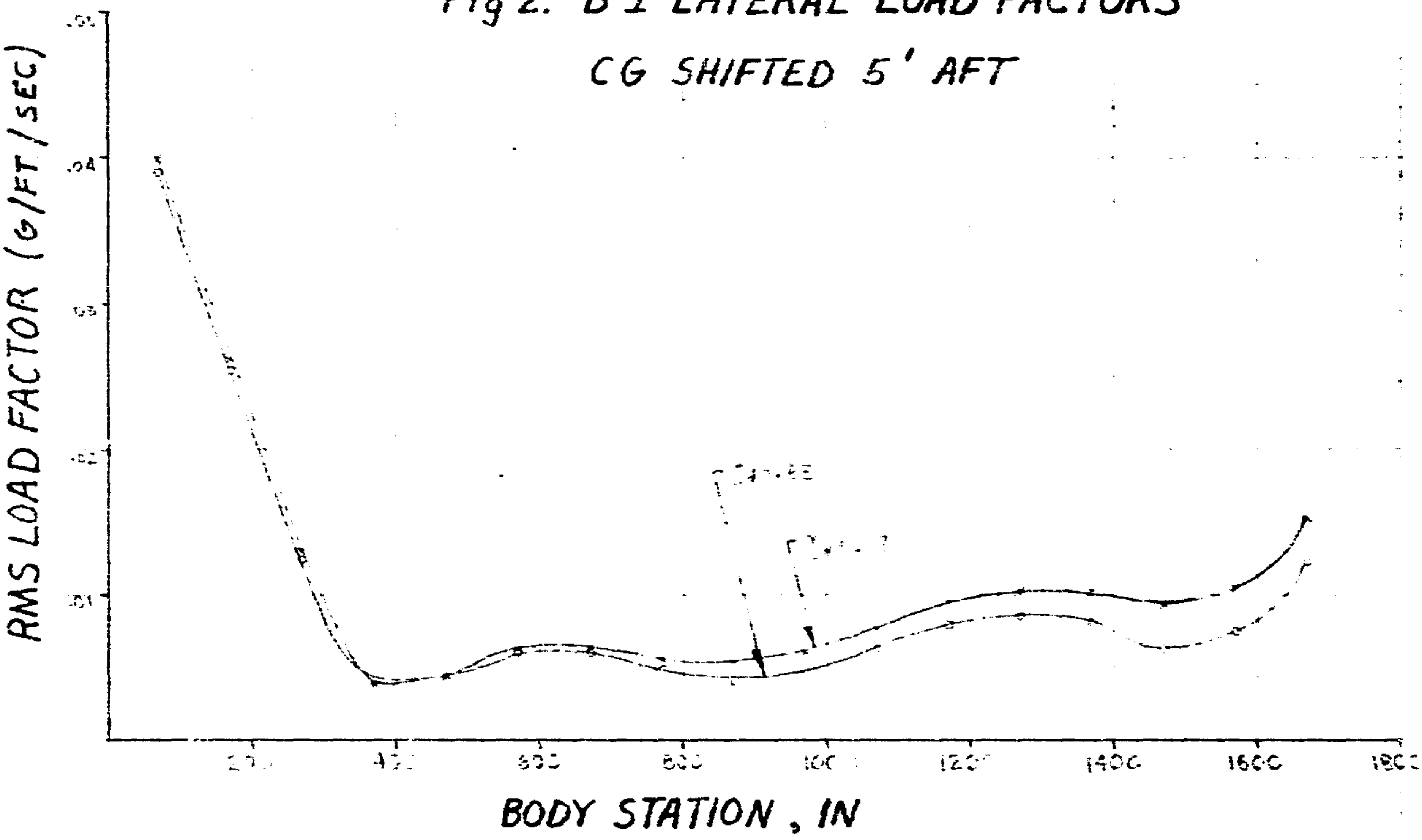


Fig 2. B-1 LATERAL LOAD FACTORS

CG SHIFTED 5' AFT



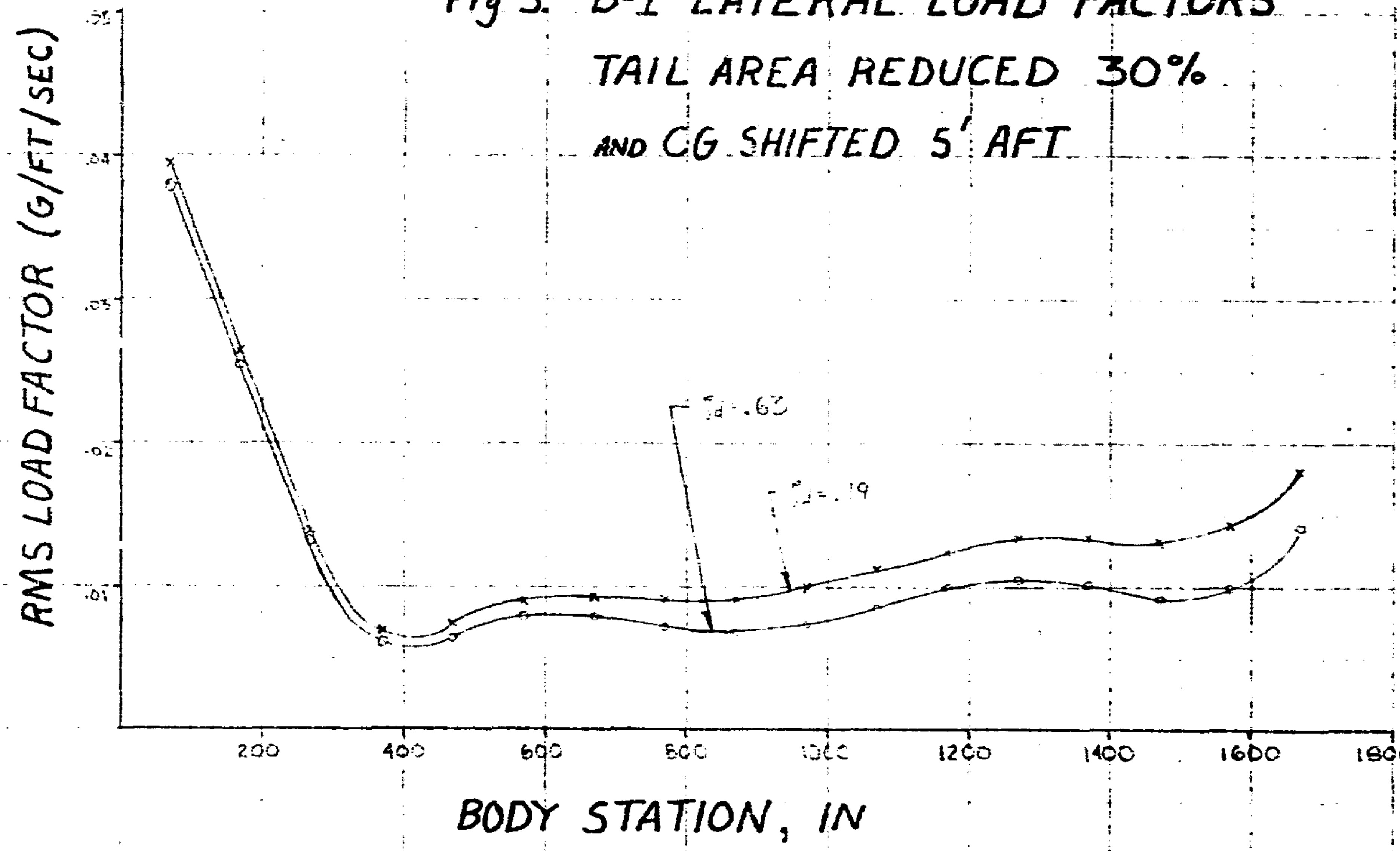
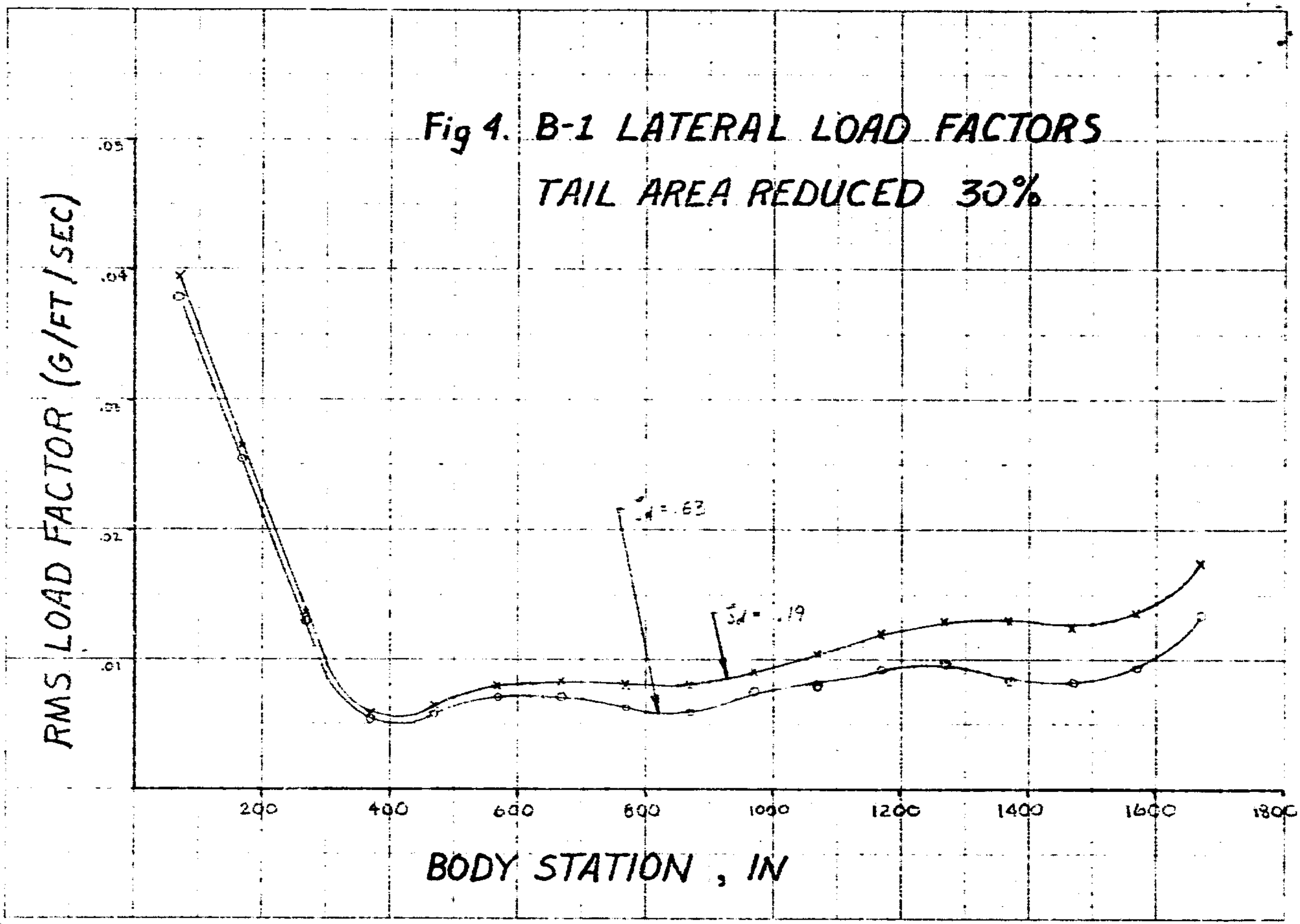


Fig 3. B-1 LATERAL LOAD FACTORS
TAIL AREA REDUCED 30%
AND CG SHIFTED 5' AFT

Fig 4. B-1 LATERAL LOAD FACTORS
TAIL AREA REDUCED 30%



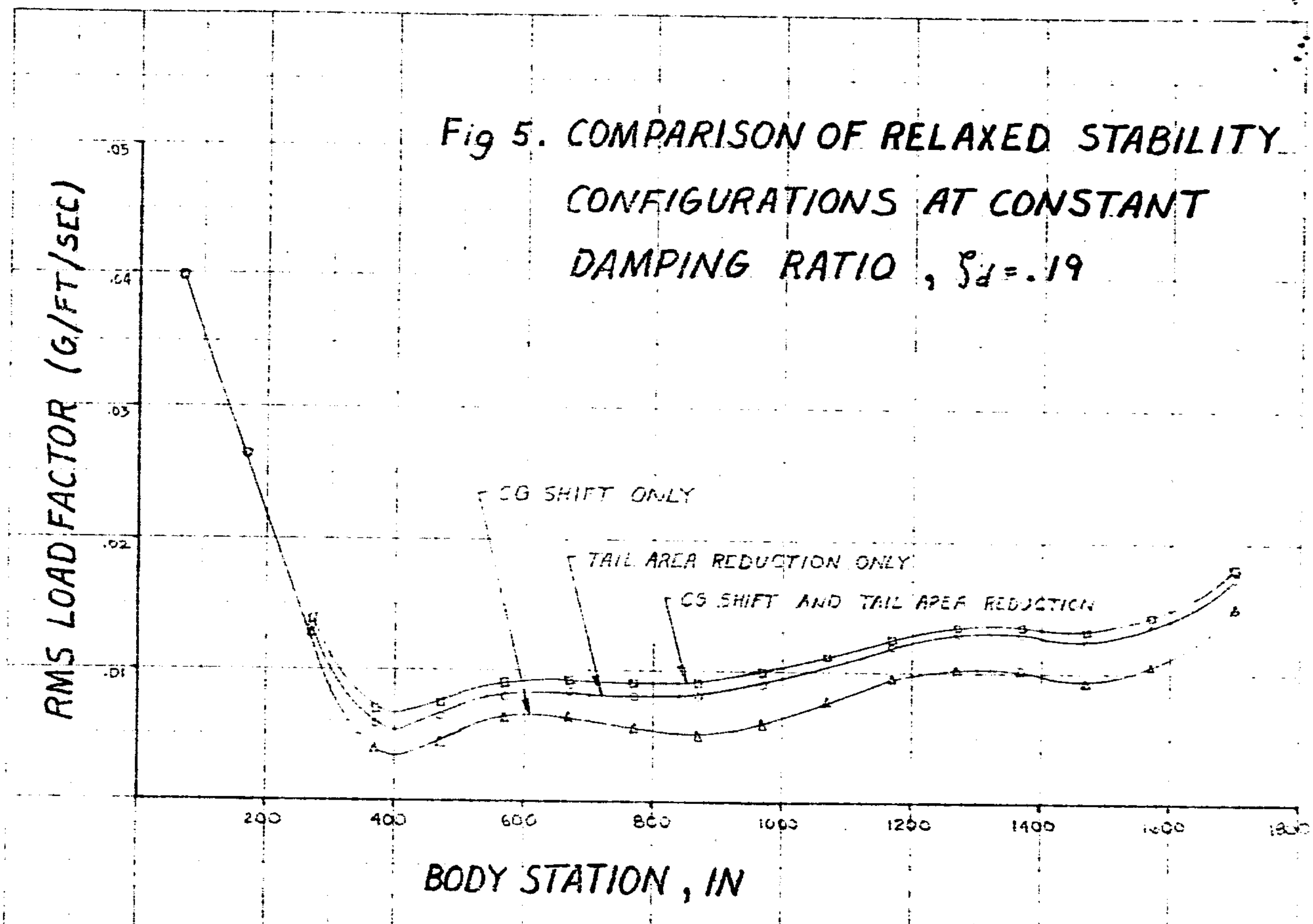


Fig 5. COMPARISON OF RELAXED STABILITY CONFIGURATIONS AT CONSTANT DAMPING RATIO, $\zeta_d = .19$

Fig. 5B. DAMPING RATIO $\zeta_d = .63$